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SUMMARY OF TRANSONIC COMPRESSOR RESEARCH

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The information provided in this report is a summary of the research activities completed during the period of July 1974 to January 2002. Complete details on these research activities are provided in the 48 technical reports and 26 journal articles that were generated throughout the effort. A listing of these reports and journal articles are provided in the appendix of this summary. Seven distinct research efforts (all documented by the reports and journal articles identified in the appendix) were pursued during the reporting period.

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INTRODUCTION

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SUMMARY OF RESEARCH ACTIVITIES

1. Supersonic Compression Stage Development

During this effort a single-stage supersonic compressor was designed and evaluated through experiments. The compressor was designed for an over-all stage total pressure ratio of 3 to 1 at an isentropic efficiency of 82 percent. Design tip speed was 1600 ft/sec at standard conditions and the inlet hub/tip radius ratio was 0.75. The compressor tested was designed for diffusion levels (greater than 0.5) beyond the range of past experience in both rotor and stator. Design goals were not met in this study. At design speed the flow rate was 30% low, total pressure ratio was 2.63, and the efficiency was 68%. The main conclusion drawn from the collective body of data was that the behavior of the rotor deviation angle as a function of incidence was such that, as the rotor was forced to operate at high incidence angles at part speed, the relative turning angle across the rotor was reduced too rapidly for the compressor to recover as design speed was approached. The rotor was redesigned with splitter vanes between each of the principal rotor airfoils. The splitter vane consisted of an airfoil located circumferentially mid-way in the downstream half of each rotor blade passage and extending full span. The addition of splitter vanes greatly improved the performance of the rotor, with the flow rate only 12 percent low, and rotor efficiency 5 points low, and stage total pressure ratio at 2.77. It was concluded that a splitter vane carefully designed in the cascade plane might produce much lower losses than reported.

2. High-Through-Flow Compression Stage Development

During this research effort the potential to achieve high-flow per compressor frontal area was explored. A single stage axial compressor was designed and tested with the following performance objectives: 1. Flow per frontal Area- 39.7 lb/sec/ft^2, 2. Rotor tip speed: 1500 ft/sec, 3. Rotor total pressure ratio 1.97, 4. Rotor isentropic efficiency of 86.9%. The results of the tests indicated that all of the rotor and stage design goals were achieved or exceeded. The method of airfoil optimization chosen where the work distribution in the rotor, and angular momentum distribution in the stator, were adjusted to achieve a minimum static pressure gradient, was a contributing factor to the success of this program. In addition the choice of the axial velocity ratio across the rotor of less than 1.0 did an excellent job of controlling shock losses. Also the swept leading edge of the stator hub had a major impact on the design. The strong sweep at the hub and the mild sweep at the tip have forced the fluid with the least momentum toward mid passage where it is the most harmless. The stage exhibited certain aeromechanical aspects of behavior that could be judged impractical in a blade system designed for some service applications. As a result the rotor was redesigned to improve on the aeromechanical behavior. The rotor leading and trailing edge thicknesses were doubled. The rotor maximum thickness-to-chord ratio distributions were varied.

3. Tip Clearance and Vortex Generators on Transonic Compressor Performance

This research study investigated a series of minor parametric modification to the compressor stage described in 2. The parametric modifications considered were three casing vortex generators configurations, three separate rotor tip running clearances, and one rotor tip vortex generator configuration. Both casing vortex generators and a reduction of rotor tip clearance produced improvements in performance visible over the full span, not localized at the tip. No sign of optimum clearance was evident at practical

levels of running clearance. In spite of the high rotor diffusion levels, the effect of rotor vortex generators was minimal. It was concluded that a rotor leading edge flow separation existed with reattachment occurring behind so close to the vortex generators that they had no opportunity to act.

4. Maximum Thickness Location and Cascade Area Ratios in Transonic Rotors

During the study 5 different transonic compressor rotors were designed and tested with parametric variation in max thickness location and cascade area ratios. Transonic compressor rotor performance is sensitive to variations in chordwise location of maximum thickness. In this study rotor blade max thickness location was moved forward in two increments from the nominal 70 percent to 55 and 40 percent chord length. At design speed the rotor with its maximum thickness located at 55 percent chord length attains the highest peak efficiency among the three rotors, but has the lowest stall margin. The difference in performance between the two rotors with the most forward locations of max thickness can be attributed to the higher shock losses that result from the increased leading edge "wedge angle" as the maximum thickness is moved closer to the leading edge. Based on rotor peak efficiency the optimum location of maximum thickness was found to be at a location of 55 to 60 percent chord for such low aspect ratio transonic rotors. The cascade throat area study revealed that tight throat margins result in increased high-speed efficiency with lower part speed performance. Higher internal contraction expressed as throat-to-mouth area ratio, also resulted in increased design point peak efficiency, but also at the cost of low speed performance. Reducing the trailing edge effective camber, expressed as throat-to-exit area ratio, resulted in improvement in peak efficiency levels without significantly lowering the stall line. The best high speed efficiency was obtained by the rotor with a tight throat margin and highest internal contraction, but its efficiency was lower at part speed.

5. High-Stage-Loading Compressor Concepts

This research effort had the goal of achieving high levels of compressor stage loading such that high overall pressure ratios could be achieved with a minimal number of stages. The design criteria for the stage was a pressure ratio of 2.2 with corrected tip speeds of 1250ft/sec and flow per unit annulus area of 40.0 lb/sec/ft^2. The rotor tip and stator hub diffusion factors were 0.52. Two single stage configurations were designed and tested. The concepts explored during this study were transitioned to an ongoing development program.

6. Swept Aerodynamics for Transonic Compressors

During this effort a new three-dimensional model was developed for the estimation of shock losses in compressor blade rows near peak efficiency. It was found that leading edge sweep if employed as a design variable could minimize shock losses and maintain rotor blade structural integrity. With this model 5 rotors were designed with different methods of sweeping the leading edge of the rotor blade. They included backward (aft) sweep through leading edge variation, forward sweep through leading edge variation, sweep though circumferential lean only and sweep through both leading edge variations and circumferential lean. For the aft swept transonic rotor configuration the experimental results demonstrated that shock loss reductions predicted by the model were exceeded. However, near the tip the loss model under predicts the loss because the shock geometry assumed by the model remains swept in this region while numerical results show a more normal shock orientation. Design specific flow rate of 43.98 lbm/sec/ft^2 was achieved. Design pressure ratio fell short of the 2.04 goal by 0.07 and the efficiency was 3 points below prediction, though very high at 91.

7. **Stage Matching and Blade Row Interactions in Transonic Compressors**

Detailed experimental studies obtained during this phase of the program quantified, for the first time, the significance of blade row spacing on aerodynamic loss development in transonic compression systems. It was determined that for blade-row spacings below 26% stator chord a significant increase in loss occurs due to unsteady interactions effects. This increase in loss results in over one point drop in aerodynamic efficiency and up to 3% reduction in flow swallowing capability. Both of theses performance indices are of significant level to require proper accounting during design. In addition the experimental study demonstrated that the dynamic loading on the upstream stator as a result of these close spacings is far greater than loading imposed be the rotor upstream of the stator. Particle Image Velocimetry (PIV) studies were carried out to identify the kinematics of the complex interaction between a rotor bow shock and stator wake. This was the world's first PIV investigation of this complex interaction phenomenon in a transonic compressor. The PIV results demonstrate that the rotor drives the wake shedding at the blade pass frequency instead of the natural shedding frequency of the IGV. It was also found that the velocity field entering the rotor varies considerably with rotor blade position for the closer spacing configurations. This variation in magnitude and direction of the flow field can have severe consequences on the rotor's ability to generate work.

APPENDIX: Reports and Journal Articles

Technical Reports

#	AD #	TR NUMBER	DATE	TITLE
1	**0778844**	ARL TR 74-0001	Jan-74	Test of an Axial Compressor Stage Designed for a Total Pressure Ratio of Three to One
2	**0786025**	ARL TR 74-0110	Aug-74	Design of a Rotor Incorporating Splitter Vanes for a High Pressure Ratio Supersonic Axial Compressor Stage
3	**A008127**	ARL 75 0052	Apr-74	On the Treatment of Body Forces in the Radial Equilibrium Equation of Turbomachinery
4	**A009880**	ARL TR 75-0104	Apr-75	Calibration Results for Stationary Pressure Rakes Sensing Yaw Angle Downstream of an Axial Compressor Stage
5	**A014732**	ARL TR 75-0165	Jun-75	Test of a Supersonic Axial Compressor Stage Incorporating Splitter Vanes in the Rotor
6	**A026675**	ARL TR 75-0192	Jun-75	Data Reduction of Single Stage Compressor
7	B016386	AFAPL-TR-76-59	Oct-76	Design of a 1500 ft/sec, Transonic, High-Through-Flow, Single-Stage Axial Flow Compressor with Low Hub/Tip Ratio
8	B016506	AFAPL-TR-76-92	Oct-76	Investigation of a 1500 ft/sec, Transonic High-Through-Flow, Single Stage Axial-Flow Compressor with Low Hub/Tip Ratio
9	B042609	AFAPL-TR-79-2078	Sep-79	Redesign of a Rotor for a 1500 ft/sec, Transonic, High-Through-Flow, Single-Stage Axial-Flow Compressor with Low Hub/Tip Ratio
10	B046397	AFAPL-TR-79-2096	Dec-79	Design of a1250 ft/sec, Low Aspect Ratio, Single-Stage Axial-Flow Compressor
11	B045322	AFAPL-TR-79-2105	Jan-80	Axial Compressor Performance Improvement Program
12	B050857	AFWAL-TR-80-2042	Jun-80	Investigation of a High-Through-Flow, Single-Stage Axial-Flow Compressor with Casing Vortex Generator Configuration "A" (Configuration 1A)
13	B050858	AFWAL-TR-80-2054	Jun-80	Investigation of a High-Through-Flow, Single-Stage Axial-Flow Compressor with Casing Vortex Generator Configuration "B" (Configuration 1B)

14	B059621	AFWAL-TR-80-2079	Apr-81	Investigation of a High-Through-Flow, Single-Stage, Axial-Flow Compressor with Tip Clearance Increased 0.010 inch (Configuration 2)
15	B059617	AFWAL-TR-80-2080	Apr-81	Investigation of a High-Through-Flow, Single-Stage, Axial-Flow Compressor with Tip Clearance Increased 0.010 inch and Casing Vortex Generator Configuration "A" (Configuration 2A)
16	B058230	AFWAL-TR-80-2103	Apr-81	TESCOM Single-Stage Configuration Performance Data Reduction
17	A102170	AFWAL-TR-81-2020	May-81	Determination of Aerodynamically Adequate Fillet Geometry in Turbcompressor Blade Rows
18	B059620	AFWAL-TR-81-2024	Apr-81	Investigation of a High-Through-Flow, Singe-Stage, Axial-Flow Compressor with Tip Clearance Increased 0.010 inch and Casing Vortex Generator Configuration "C" (Configuration 2C)
19	B060879	AFWAL-TR-81-2025	Apr-81	Investigation of a High-Through-Flow, Singe-Stage, Axial-Flow Compressor with Tip Clearance Increased 0.020 inch and Casing Vortex Generator Configuration "C" (Configuration 3C)
20	B059689	AFWAL-TR-81-2026	Apr-81	Investigation of a High-Through-Flow, Singe-Stage, Axial-Flow Compressor with Tip Clearance Increased 0.010 inch and Casing Vortex Generator Configuration "A" (Configuration 3A)
21	B059690	AFWAL-TR-81-2027	Apr-81	Investigation of a High-Through-Flow, Singe-Stage, Axial-Flow Compressor with Tip Clearance Increased 0.010 inch and Casing Vortex Generator Configuration "B" (Configuration 2B)
22	B059642	AFWAL-TR-81-2028	Apr-81	Investigation of a High-Through-Flow, Singe-Stage, Axial-Flow Compressor with Tip Clearance Increased 0.020 inch and Casing Vortex Generator Configuration "B" (Configuration 3B)
23	B059618	AFWAL-TR-81-2029	Apr-81	Investigation of a High-Through-Flow, Singe-Stage, Axial-Flow Compressor with Tip Clearance Increased 0.020 inch (Configuration 3)
24	A106676	AFWAL-TR-81-2078	Sep-81	A Computer Program for Variable Geometry Single-Stage, Axial-Compressor Test Data Analysis (UD0400)
25	B068306	AFWAL-TR-82-2070	Aug-82	Investigation of a High-Through-Flow, Single-Stage, Axial-Flow-Compressor with Tip Clearance Increased 0.200 inch, Rotor Tip Vortex Generators, and Casing Vortex Generators Configuration B, Configuration 3.1.B
26	B068098	AFWAL-TR-82-2071	Sep-82	Investigation of a High-Through-Flow, Single-Stage, Axial-Flow-Compressor with Tip Clearance Increased 0.200 inch, Rotor Tip Vortex Generators, Configuration 3.1
27	B068926	AFWAL-TR-82-2074	Sep-82	A Computer Program For Axial Compressor Design (UD0300M)

28	A124928	AFWAL-TR-82-2079	Dec-82	Revision of the Shock Loss Re-estimation Procedure of Program UD0300 Utilizing a Three Dimensional Shock Model
29	A122027	AFWAL-TR-82-2080	Sep-82	A Computer Program for the Determination of the Flat Plane Projection of a Printed Circuit Type Strain Gage Lead
30	B072181	AFWAL-TR-82-2131	Feb-83	Investigation of a High-Stage-Loading, Low-Aspect-Ratio Single-stage Compressor (TESCOM Configuration 1B)
31	B074643	AFWAL-TR-83-2016	Feb-83	Investigation of a High-Stage-Loading, Low-Aspect-Ratio Single-stage Compressor (TESCOM Configuration 1A)
32	B073611	AFWAL-TR-83-2027	May-83	Design of a 1250 ft/sec, Low-Aspect-Ratio, Two-Stage, Axial-Flow Compressor
33	B089186	AFWAL-TR-84-2052	Sep-84	Design of a Rotor for a 1500 ft/sec, Transonic, High-Through-Flow Compressor with Low Hub/Tip Ratio and Swept Leading Edge
34	B116562	AFWAL-TR-86-2013	Feb-87	Design of a Rotor Incorporating Meridional Sweep and Circumferential Lean for Shock Loss Attenuation
35	B128860	AFWAL-TR-88-2107	Nov-88	Parametric Blade Study Test Report Rotor Configuration No.1
36	B128861	AFWAL-TR-88-2108	Nov-88	Parametric Blade Study Test Report Rotor Configuration No.2
37	B128862	AFWAL-TR-88-2109	Nov-88	Parametric Blade Study Test Report Rotor Configuration No.3
38	B128863	AFWAL-TR-88-2110	Nov-88	Parametric Blade Study Test Report Rotor Configuration No.4
39	B128864	AFWAL-TR-88-2111	Nov-88	Parametric Blade Study Test Report Rotor Configuration No.5
40	B128865	AFWAL-TR-88-2112	Nov-88	Parametric Blade Study Test Report Rotor Configuration No.6
41	B128866	AFWAL-TR-88-2113	Nov-88	Parametric Blade Study Test Report Rotor Configuration No.7
42	A206951	AFWAL-TR-89-2005	Mar-89	Two Axial Compressor Designs for a Stage Matching Investigation

43	B136767	WRDC-TR-89-2107	Jun-89	Splitter Blade Design Using Program UD0300M
44	A242760	WL-TR-91-2003	Jul-90	KPLOT - A Computer Program for Contour Plotting High Frequency Static Pressure Experimental Data
45	A242870	WL-TR-91-2004	Jul-90	Cgraph - A Fortran Callable Graphics Library
46	A291275	WL-TR-93-2058	Dec-94	Characterization of Stall Inception in High-Speed Single-Stage Compressors
47	A321086	WL-TR-96-2134	Oct-96	Vibrational Analysis of a 1/4" Stainless Steel Kulite Probe
48	B238602	AFRL-PR-WP-TR-1998-2040	Mar-98	Swept Rotor Study

-Journal Articles

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